

Effect of Lime on Silty Clay for Use in Road Construction

Batran Sidick Adam^{1*}, Abdallah Ban-Nah Mahamat², Waibaye Adoum¹,
Nadjitonon Ngarmaim³, Ali Al-Hdj Allahou¹

¹Department of Civil Engineering, National School of Public Works of N'Djamena, N'Djamena, Chad

²Department of Mechanical Engineering, National Higher Institute of Science and Technology of Abeche, Abeche, Chad

³Faculty of Exact and Applied Sciences, University of N'Djamena, N'Djamena, Chad

Email: *batran2005@yahoo.fr

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Abstract

This study evaluates the effect of quicklime on the geotechnical properties of silty clay used in road construction. The addition of 2% to 10% quicklime modified the grain size through flocculation, thereby improving the performance properties of the material. The mechanical properties of the material improved with 2% to 4% quicklime. Above a content of 4%, considered to be the fixing point of the lime, the mechanical properties decreased and no longer improved. The CBR indices obtained with 2% to 6% lime were above the minimum of 30% and could be used in road foundation layers. The rigidity of the material obtained after treating the soil with quicklime allows the material obtained after mixing to perform well in hot weather, without deformation or rutting when subjected to traffic. This is because lime binds the fine clay particles into much larger particles after flocculation, which are more or less impermeable on the surface and reduce material degradation due to crumbling and abrasion, which are responsible for road surface deterioration. Subsequently, the friction of the grains under the stress exerted by the hammering of the tyres consolidates the mechanical bonds during setting, slowing down the wear of the particles that generate plastic fines.

Keywords

Silty Clay, Geotechnical Properties, Quicklime, CBR Index, Rutting, Flocculation

1. Introduction

A country's economic and social development depends on its integration and accessibility through road construction. In some African countries, road transport

remains dominant, accounting for more than 80% of inter-city or inter-state freight traffic, and is often the only means of access to rural areas [1]. The city of N'Djamena is currently undergoing considerable development due to a growing population combined with rural exodus, forcing the government to invest heavily in urban road construction. This expansion is significant given the emergence of new neighborhoods linked to urbanization issues in the city. The construction of several roads in a city plays a decisive role in the smooth flow of goods and people [2]. Building a road in a city is a delicate operation given the regulatory framework that defines the scope of the urban road network, with the associated problems, sometimes linked to expropriation, the relocation of water and electricity networks, etc. [3]. Road construction involves the use of selected materials in the pavement structure, in accordance with best practices and applicable standards. However, some African countries do not have their own standards, and the choice of materials for the different layers of the pavement is based on foreign standards (European NE standards, French NF standards, American ASTM standards, etc.) [4] [5]. These standards do not favor the use of local materials, as they were designed for materials that are often specific to their climate. Several studies show that materials deemed unsuitable for construction according to these standards have performed better than those approved by the same standards [1]. Exclusive reference to foreign standards does not reflect the local environment and prevents the promotion of local resources with their specific characteristics [4] [6]. Furthermore, the use of these standards requires laboratories equipped with the necessary equipment to carry out laboratory and on-site tests, which requires qualified personnel who are not always available [7]. This is why laboratory tests prior to the construction of a road structure are not always carried out. This lack of qualified technicians has an impact on the quality control of materials, often leading to premature deterioration of structures [4] [6]. The scarcity of construction materials suitable for direct use in road construction near the city of N'Djamena has led to the search for alternative solutions for this environment. In this city and its surroundings, only clay-loam soils are found, which are not suitable for construction according to standards, but whose use would reduce construction costs. However, clay-loam soils are noble soils that contain a significant proportion of clay or silt, but have poor road properties. These soils are not stable in the face of climatic variations. They swell and become plastic during the rainy season, which can make vehicle traffic difficult or even impossible. This behavior, therefore, makes their extraction and use in road construction difficult [8]. The proposed alternative solution, which consists of using these soils, will reduce the costs associated with the environmental impact of road maintenance and construction. However, the use of unconventional natural or recycled fine soils can be an asset if it is preceded by the necessary geotechnical studies [9]-[11]. Indeed, several studies show that the bearing capacity of fine soils unsuitable for road construction can be improved by adding hydraulic binders (lime, cement). Soil treatment with binders is a proven and well-developed technique that has been growing in popularity for over twenty years [12]. The use of a soil-lime mixture is economical given the price of cement

in Chad. Lime is the most suitable binder for treating clay soils compared to cement, as it is cheaper and available in all markets throughout the country.

The incorporation of lime into the soil after adding water produces a homogeneous material after mixing, giving it new properties with the desired performance characteristics [8]. This treatment method saves energy overall by reducing the transport of rock materials; it is environmentally friendly as it reduces greenhouse gas emissions; it protects the road network near the construction site and minimizes disruption to road users and local residents. Several studies published in the literature indicate that incorporating lime into fine soils improves their geotechnical properties, which has several advantages. Lime improves the service life, bearing capacity, workability and application of the soil, as well as its mechanical behaviour [13]-[15]. The behavior of the soil-lime mixture depends not only on its particle size and mineralogy, but also on its microstructure. Several studies show that treating fine soils with lime simultaneously causes four fundamental reactions: cation exchange, flocculation and agglomeration, lime carbonation and pozzolanic reaction, which improve geotechnical properties (Atterberg limits, swelling potential, dry density, compressive strength, CBR index, shear strength, etc.) [16]-[18]. The behavior of the soil-binder combination depends on the granularity and mineralogy of the soil, the type and clay content, the lime content, and the curing time and temperature. Several studies show that clay activity can provide information on the nature of the clay present in a soil [11]. Active soils are capable of absorbing large amounts of water, which makes them unstable for construction. To compensate for this instability, stabilizers are used to react with the soil and occupy the available chemical bonds. However, if the soil is inactive, it does not absorb water. Chad has significant deposits of silty clay that could be used in road construction. Despite the diversity of studies, these have not exhausted the subject, and it will always be important for each soil-lime combination to carry out the necessary tests. To our knowledge, the effect of lime on the geotechnical properties of clayey-silty soils in Chad has not yet been reported.

The objective of this work is to characterize a silty clay treated with quicklime for use in road construction. To this end, the geotechnical properties of the silty clay and soil-lime mixtures will be optimized, as well as the activity of the clay fraction and its intrinsic properties.

2. Materials and Methods

2.1. Materials

Gaoui, a village founded in the 19th century and located eighteen (18) kilometers northeast of N'Djamena, whose geographical coordinates are: 15.172460°N and 12.138719°E. Soil samples were taken at depths between 1.5 and 2 m, placed in bags and transported to the laboratory of the National School of Public Works.

The soils studied come from fine-grained sedimentary rocks, less than 5 µm in size, composed largely of specific minerals, generally silicates, of more or less hydrated aluminum, which have a layered structure explaining their plasticity [19]

(see **Table 1**).

Table 1. Chemical composition of soil [19].

Oxydes	SiO ₂	Al ₂ O ₃	CaO	Fe ₂ O ₃	MgO	K ₂ O	SO ₃	Na ₂ O	P.F	Total
Mass %	52.57	20.72	Traces	8.14	2.84	6.14	0.18	Traces	8.86	99.45

Quicklime was purchased on the local market. It was used in combination with clay in proportions of (2%, 4%, 6%, 8%, 10%) to improve the geotechnical properties of the soil for road construction. However, quicklime was used with great caution, as excessive amounts could have a negative impact on the human body and the environment.

Lime is a whitish powder obtained by thermal decomposition (pyrolysis) of limestone. Chemically, it is calcium oxide (CaO) containing varying amounts of about 83%, magnesium oxide (MgO) about 2% and carbon dioxide (CO₂) about 3% but the common designation of lime can encompass different chemical states of this product [20] [21].

Mixtures of soil and quicklime at 0% (natural soil), 2%, 4%, 6%, 8% and 10% by dry weight of the sieved soil were prepared by carefully mixing the sieved soil and lime until homogeneous mixtures were obtained. The mixture was then left in closed bags for one hour before being tested, to allow the lime to act on the fine clay particles present in the soil

2.2. Methods

Based on the physical and chemical properties of the grains, the raw soil and mixtures (2%, 4%, 6%, 8% and 10%) are classified according to the AASHTO T88-70 [22] and USCS [23] classifications. Origin Pro 2019b software was used in the process of developing correlations between the intrinsic properties of the soil and the data processing obtained in the laboratory. In the laboratory, the soil clods were crushed and sieved to retain only grains with a diameter of less than 2 mm, then the soil was placed in an oven for 24 hours. The methodology used included identification tests (grain size analysis and sedimentation, Atterberg limits, activity, specific surface area, cation exchange capacity), bearing capacity tests (Proctor, CBR) and classification tests on natural soils and laboratory mixtures.



Weighing of materials



Materials put into the plastic



Powder of sieved lime

Figure 1. Weighing and storage of samples.

The weight of the soil and lime in the mixture was weighed beforehand, then the two materials were mixed manually in a dry state until the mixture was as homogeneous as possible. The mixtures thus prepared were then placed in plastic bags, kept and stored at room temperature for one hour, as shown in **Figure 1**.

The following tests were carried out:

Particle size analysis by sieving and sedimentation were determined in accordance with standards NF P94-056 and NF P94-057 [24] [25].

The particle size fraction is derived from the recommendations of particle size nomograms, which consider clays to be particles smaller than <0.002 mm, silts to be particles between 0.002 and 0.06 mm, and sands to be particles between 0.06 and 2 mm. The particle size distribution of a soil is characterized by the coefficient of uniformity C_u and the coefficient of curvature C_c , defined by the following formulas:

D_x is the particle size corresponding to $x\%$ by weight of the sieving.

$$C_u = \frac{D_{60}}{D_{10}} \quad (1)$$

$$C_c = \frac{(D_{30})^2}{D_{10} \times D_{60}} \quad (2)$$

Atterberg limits (plasticity limit, liquidity limit, plasticity index) apply to fine particles smaller than 400 μm and are determined in accordance with standard NF P94-051 [26].

Methylene blue value (MBV) is used in geotechnics to characterize the quality of soils, in particular their fine clay content and their sensitivity to water. It is defined by standard NF P94-068 [27].

Specific surface area (SSA) refers to the actual surface area of a soil particle. This parameter allows the interpretation of physical characteristics such as shrinkage and swelling potentials. It is determined by the following formula:

$$\text{SSA} = 20.93 \times \text{MBV} \quad (3)$$

SSA (m^2/g): specific surface area, MBV ($\text{g}/100\text{g}$): methylene blue value.

Cation exchange capacity (CEC) is the number of cations in the double layer that can be easily replaced or exchanged by other cations per 100 grams of soil. It is also determined by the following formula:

$$\text{CEC} = \frac{\text{MBV} \times 1000}{374} \quad (4)$$

Soil activity "Ac" is characteristic of the mineral composing the fine particles. It is defined as the ratio between the plasticity index (PI) and the clay fraction CF < 0.002 mm [28].

$$\text{AC} = \frac{\text{PI}}{\text{CF}(\%) < 0.002 \text{ mm}} \quad (5)$$

Ac: Soil activity; PI: plasticity index; CF: clay fraction.

Natural water content, defined according to standard NF P94-050 [29], is the

ratio between the weight of water contained in the soil and the weight of its dry components, after drying in an oven at 105 °C.

Modified Proctor test, defined according to standard NF P94-093 [30], is used to determine the optimum water content, denoted W_{opt} , and the maximum dry density of the soil, denoted γ_{dmax} , in order to achieve the best possible compaction of a given soil.

California Bearing Ratio (CBR), defined in accordance with standard NF P94-078 [31], is measured both on the foundation soil of a road structure and on the materials used for its construction. This test is used to determine the thickness of a roadway.

3. Results and Discussion

3.1. Results

The particle size analysis of the natural soil shows grains with a maximum size of 3 mm, which complies with the specifications of CEBTP (1980) [32], which establishes the minimum and maximum grain size of soils for the foundation layer as between 0.5 and 10 mm (Figure 2). In fact, the percentage of grains with a diameter of less than 80 μm is 92.63%, which is higher than the maximum of 30% recommended by CEBTP 1980 [32] for foundation layer materials.

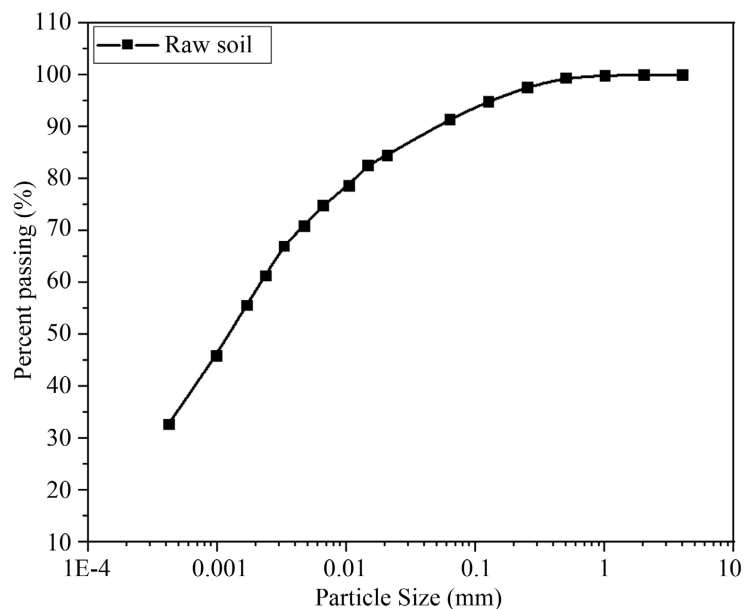


Figure 2. Distribution of grains in natural soil.

Furthermore, for soil-lime mixtures, the percentage of the fine fraction gradually decreases from 92.63% to 79.40% after adding quicklime at levels of 2% to 10% (Figure 3). The minimum percentage of 79.40% obtained with a lime content of 10% remains higher than the maximum prescribed by the CEBTP (1980) [32]. Flocculation and agglomeration of clay particles reduce the fine content by replacing monovalent ions with Ca^{2+} ions [8].

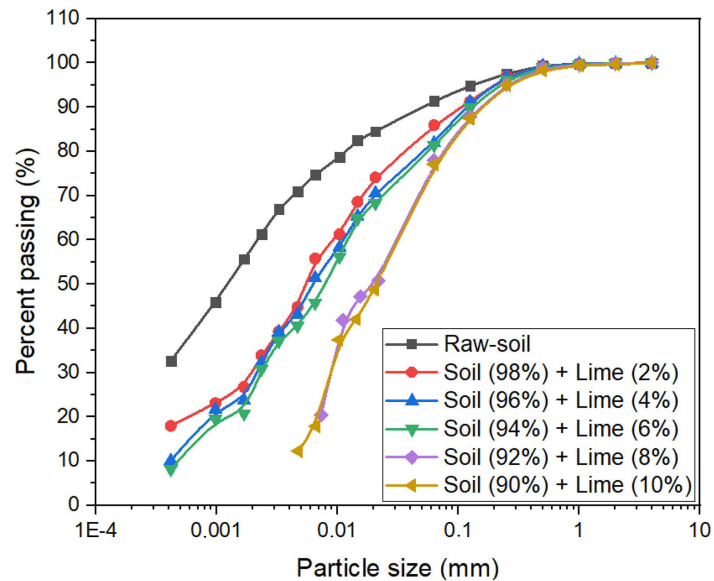


Figure 3. Distribution of natural soil grain.

According to **Figure 3**, the percentage of particles passing through the sieve for raw soil and mixtures containing 2%, 8% and 10% quicklime is greater than 10%, so that the coefficients of curvature and uniformity of their particle size distribution could not be determined. The grain sizes corresponding to D_{10} , D_{30} and D_{60} by sieved weight, deduced from the particle size distribution curves, are used to determine the uniformity coefficients C_u and curvature coefficients C_c of the mixtures containing 4% and 6% lime.

According to **Table 2**, mixtures containing 4% and 6% lime have uniformity coefficients between C_u (31.02 and 25.2 mm) and curvature coefficients between C_c (1.24×10^{-4} and 1.42×10^{-4} , respectively). Both mixtures have uniformity coefficients $C_u > 2$, which means that they have a wide particle size distribution. However, the particle size distribution of the mixtures is poorly calibrated. Their curvature coefficients are not within the recommended range ($1 < C_c < 3$).

Table 2. Curvature and uniformity coefficients.

Lime	D_{10}	D_{30}	D_{60}	C_u	C_c
4%	4.094×10^{-4}	0.002	0.0127	31.02	1.24×10^{-4}
6%	4.92×10^{-4}	0.0024	0.0124	25.2	1.42×10^{-4}

Figure 3 shows the texture of the natural soil and that of the mixtures at 2%, 4%, 6%, 8% and 10%. Quicklime significantly altered the particle size distribution of the mixtures, which were sensitive to grain size for lime contents between 2% and 10%. The improvement in the properties of the mixtures was achieved after modifying the particle size following the formation of aggregates. In other words, the lime modified the rheology of the mixtures through flocculation. The particle size fractions of clay, silt and sand are deduced from **Figure 3** and are presented in **Figure 4**.

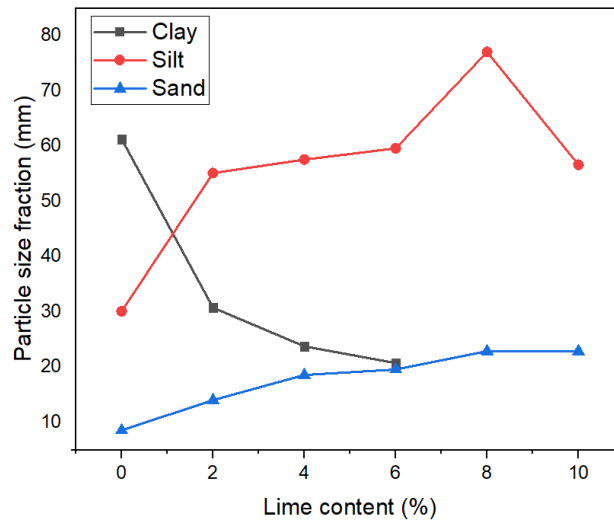


Figure 4. Effect of lime on particle size fractions.

Figure 4 shows the changes in the grain size fractions of clay, silt and sand. Lime modifies the grain size distribution of the mixtures by reducing the clay fraction from 61.69% to 20.75%, a decrease of 33.636% for lime contents between 0% and 6%. Above 6% quicklime, the clay fraction is completely neutralized, offset by an increase in the silt fraction. The silt fraction increases from 30.13% to 56.65%, representing an increase of 88.80%, for lime contents between 0 and 8%, which represents the optimal mixture, and at 10% lime, the silt content decreases. The sand fraction increases from 8.58% to 22.9%, representing an increase of 166.90%.

The flocculation of fine clay particles following the addition of lime has altered the nature of the natural soil. Lime modifies the particle size distribution by improving the physical and mechanical characteristics of natural soil. This result is consistent with that obtained by Louis Ahouet (2023) [8], who noted that the addition of lime modifies the initial particle size distribution of fine soils by forming aggregates, thereby improving the properties of the treated soil. Researchers Kavak and Akyarh (2007) [33] also found that adding lime to fine soil alters the rheology of the treated soil due to the change in grain size.

Table 3. Classification of natural soil and mixtures.

Lime (%)	LL (%)	PL (%)	PI (%)	Classification	
				AASHTO	USCS
0	64	26.74	37.26	A-6	SC
2	57.5	33.38	24.12	A-6	SC
4	54	37.54	16.46	A-6	SC
6	51.5	38.28	13.22	A-6	SC
8	49.5	40.07	9.43	A-4	SS
10	47.8	40.7	7.1	A-4	SS

SC—silty clay, SS—sandy silt, LL—liquidity limit, IP—plasticity index, PL—plasticity limit.

Based on **Figure 4** and **Table 3**, natural soil and mixtures containing 2% to 10% lime were classified according to the AASHTO [22] and USCS [23] classifications. This classification shows that natural soil and mixtures containing 2% to 6% lime are silt clays (USCS) [23] of class A-6 (AASHTO) [22], and that mixtures containing 8% to 10% lime are sandy silts (USCS) [23] of class A-4 (AASHTO) [22].

To understand the behavior of materials in the presence of water, the swelling potential and problems related to water absorption and adsorption in the material are defined in **Figure 5** and **Table 4**.

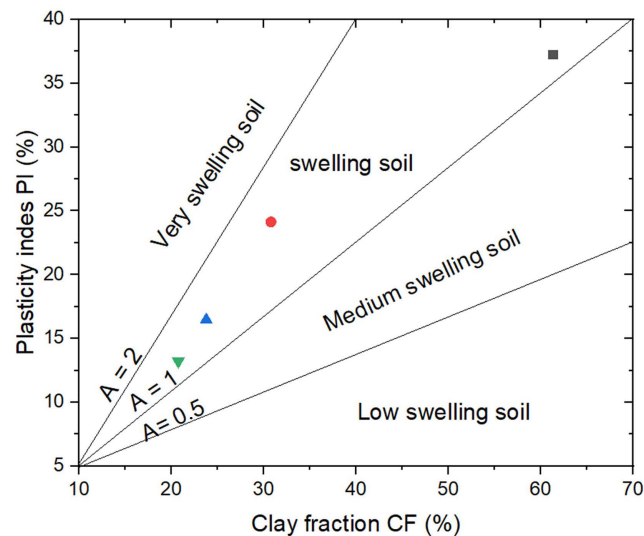


Figure 5. Swelling potential of natural soils and mixtures.

According to **Figure 5**, the natural soil and mixtures containing 2%, 4% and 6% lime show that the materials remain expansive. Indeed, the classification of this soil and these mixtures shows that we are dealing with silty clays and expansive sandy silts.

It is as if the lime were inactive on the fine clays, while the plasticity index decreases. It has been shown that soil swelling does not depend on clay content, but may depend on its mineralogy [34].

Table 4 shows the activity of natural soil and mixtures containing 2%, 4% and 6% of the material, which helps to understand the material's absorption and adsorption behavior.

Table 4. Activity of natural soil and mixtures.

Lime (%)	Clay fraction (%)	Activity	Nature
0	61.29	0.608	Inactive
2	30.78	0.784	Normal
4	23.78	0.692	Inactive
6	20.75	0.637	Inactive
8	-	-	-
10	-	-	-

According to **Table 4**, natural loamy clay has an activity of less than 0.75, the soil is inactive, and for the 2% mixture, the activity is between 0.75 and 1.25, the material has normal activity. For quicklime contents of 4% and 6%, the mixtures are inactive. The natural soil and the 4% and 6% mixtures are inactive, *i.e.* they absorb very little water. This result, based on activity, reinforces the result obtained from the swelling potential. In fact, inactive clay can refer to clay whose dehydrating properties have been exhausted and/or, more commonly in geotechnics, clay with low intrinsic activity, characterized by a low ratio between the plasticity index and the granulometric fraction of the clay, which indicates lower reactivity and limited plasticity.

Figure 6 shows the relationship between the plasticity index, which characterizes the range of water content in which the soil behaves plastically, and the methylene blue value (MBV), which characterizes the clay content (or purity) of a soil. In other words, MBV is a quantity directly related to the specific surface area of the soil and reflects the overall quantity and quality (activity) of the clay fraction.

These two parameters are related, and their evolution and correlation are illustrated in **Figure 6** and **Figure 7**.

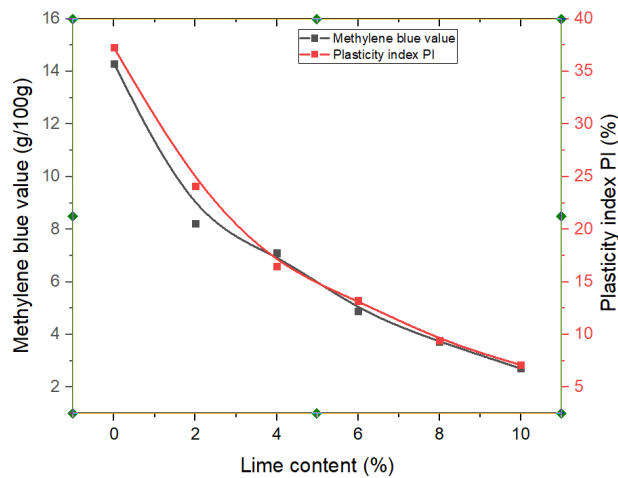


Figure 6. Effect of lime on the plasticity of fine clay soils.

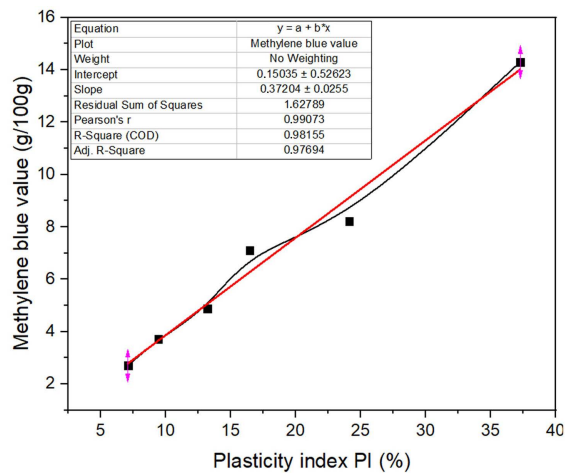


Figure 7. Methylene blue value depending on the plasticity index.

According to **Figure 6**, adding lime simultaneously reduces the plasticity index and the blue value of the soil after flocculation of the fine clay particles. These two parameters are closely related, and their correlation is illustrated in **Figure 7**.

According to **Figure 7**, the methylene blue value (MBV) and the plasticity index (PI) are correlated, and the relationship obtained is a linear function:

$$Y = a + bx \quad (6)$$

$$\text{MBV} \left(\frac{\text{g}}{100 \text{ g}} \right) = (0.15035 \pm 0.52623) + (0.15035 \pm 0.52623) \times \text{PI}(\%) \quad (7)$$

$$R^2 = 0.977$$

MBV (g/100g): methylene blue value, PI (%): plasticity index, R^2 : coefficient of determination.

In the case of clay soils, the soil blue value (MBV) test is more important than the plasticity index for classifying clays. The MBV represents the clay activity index, used in geotechnical engineering to characterize soil quality, in particular its fine clay content and sensitivity to water.

The classification of natural soils and mixtures containing 2% to 10% lime gives the results shown in **Table 5**.

Table 5. Soil classification according to the MBV.

Lime (%)	MBV	Classification
0	14.3	Very clayey soil
2	8.22	Very clayey soil
4	7.1	Clayey soil
6	4.88	Loamy clay soil
8	3.72	Loamy clay soil
10	2.71	Loamy clay soil

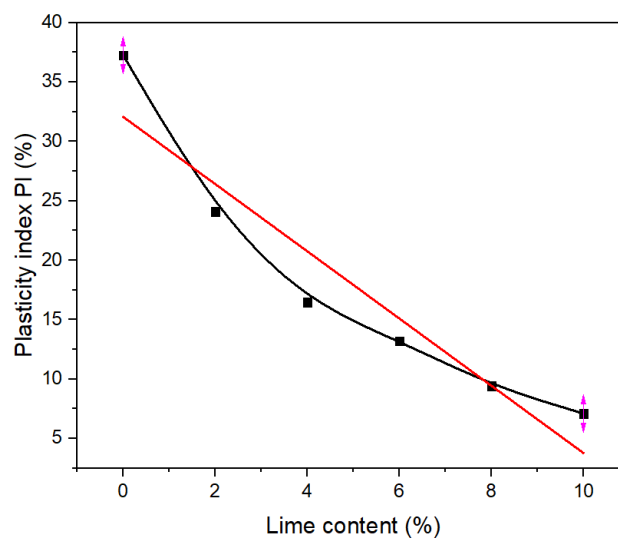


Figure 8. Evolution of the plasticity index (PI) as a function of lime content.

Table 5 shows that the classification obtained using MBV confirms that obtained using the USCS international classification [23]. The effect of quicklime on changes in plasticity in a mixture containing 2% to 10% lime, illustrated in **Figure 8**, can help to understand whether the soil-quicklime mixture obeys the law of mixtures.

Based on **Figure 8**, we can only say that the plasticity index (PI) of the soil-quicklime mixture is not truly proportional to the lime content of the mixture. Indeed, we have:

$$PI = \begin{cases} (32.08238 \pm 2.92131) + (-2.83014 \pm 0.48244)\alpha_c; R^2 = 0.896 \\ (36.22107 \pm 1.44413) + (-5.93416 \pm 0.6792)\alpha_c + (0.3104 \pm 0.06519)\alpha_c^2; R = 0.987 \end{cases} \quad (8)$$

with: PI—plasticity index of the mixture and α_c —quicklime content of the mixture, R^2 —coefficient of determination.

Based on the above, the plasticity index does not follow the law of mixtures, unlike the clay content of the mixture, *i.e.* it is not proportional to the clay content of the mixture [8]. Next, the clay content of the mixture (P_a^m) as a function of the quicklime content of the mixture is given by the following relationship:) as a function of the quicklime content of the mixture is given by the following relationship:

$$P_a^m = P_a^{sc} + (P_{PI}^m - P_a^{sc})\alpha_c \quad (9)$$

with, P_a^m , P_a^{sc} , P_{PI}^m respectively the clay content of the mixture, the clay content of the soil and the plasticity index of the mixture. In summary, if the plasticity index of the mixture was proportional to the clay content of the mixture, it would also be proportional to the lime content of the mixture [8].

Lime reduced the plasticity index (PI) by 37.26% for natural soil and by 7.1% for the mixture containing 10% quicklime, representing a decrease of 43.10% after one hour of hardening. With 4% quicklime, the plasticity index PI (16.46%) lies between the lower limit of 10% and the upper limit of 30%. In other words, the plasticity index for quicklime contents of 2% to 4% remains within the limits permitted in road construction for foundation layer materials [8] [32].

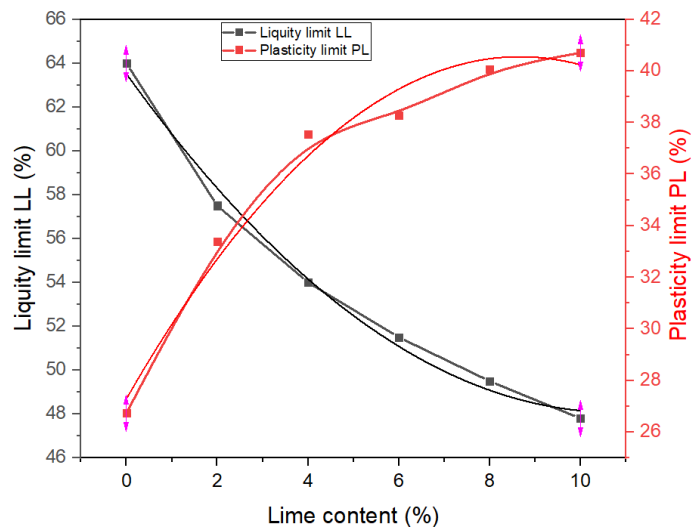


Figure 9. Evolution of the liquidity limit and plasticity limit as lime is added.

According to **Figure 9**, the addition of quicklime increases the plasticity limit (PL) by 52.21% and decreases the liquidity limit (LL) by 25.31%. The increase in the plasticity limit of loamy clay treated with quicklime may depend on the mineralogy of the clay [35] [36]. These authors, Hilt and Davidson (1960) [35] and Bell F. G. (1996) [36], found that variations in Atterberg limits did not depend on hardening time, but on lime content, and could be linked to variations in cation exchange capacity (CEC).

The evolution of plasticity limit (PL) is a polynomial function defined below:

$$Y = a + bx + cx^2 \quad (10)$$

$$PL(\%) = (27.293 \pm 0.885) + (3.059 \pm 0.416) \times LC + (-0.176 \pm 0.039) \times LC^2 \quad (11)$$

$$R^2 = 0.965$$

PL (%): plasticity limit, LC (%): Lime content, R^2 : Coefficient of determination
The evolution of liquidity limit (PL) is a polynomial function defined below:

$$Y = a + bx + cx^2$$

$$LL(\%) = (63.514 \pm 0.613) + (-2.875 \pm 0.288) \times LC + (0.139 \pm 0.028) \times LC^2 \quad (12)$$

$$R^2 = 0.987$$

LL (%): liquidity limit, LC (%): lime content, R^2 : coefficient of determination.

The changes observed in the evolution of Atterberg limits in **Figure 9** may therefore depend on the evolution of the specific surface area and cation exchange capacity of the materials defined in **Figure 10**.

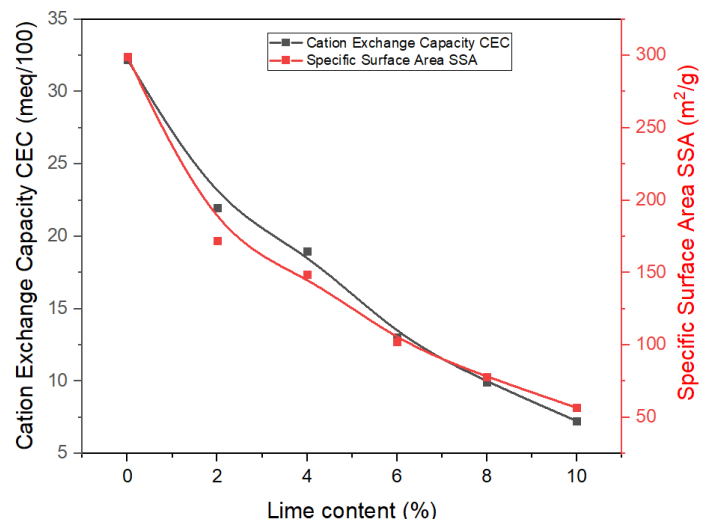


Figure 10. Effect of lime on specific surface area and cation exchange capacity cationic (CEC).

According to **Figure 10**, the specific surface area (SSA) and cation exchange capacity (CEC) of the clay fraction of the soil decrease with the addition of quicklime. The authors Herzog and Mitchell (1963) [37] and Diamond and Kinter (1965) [38] found in their work that the flocculation and agglomeration of clay particles into stable aggregates were likely to alter the cation exchange capacity

(CEC). Given that the specific surface area (SSA) and cation exchange capacity (CEC) are correlated (Figure 11), it can also be said that flocculation and agglomeration of grains also alter the specific surface area.

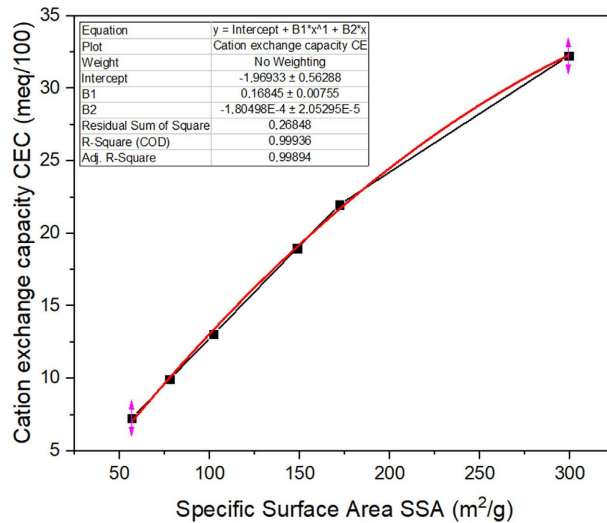


Figure 11. Correlation between SSA and CEC.

According to Figure 11, the correlation obtained between cation exchange capacity and specific surface area is a polynomial function:

$$Y = a + bx + cx^2$$

$$\text{CEC} = (-1.969 \pm 0.563) + (0.168 \pm 0.008) \times \text{SSA} + (-1.805E-4 \pm 2.053E-5) \times \text{SSA}^2 \quad (13)$$

$$R^2 = 0.999$$

CEC (meq/100): cation exchange capacity, SSA (m²/g): specific surface area, R²: coefficient of determination.

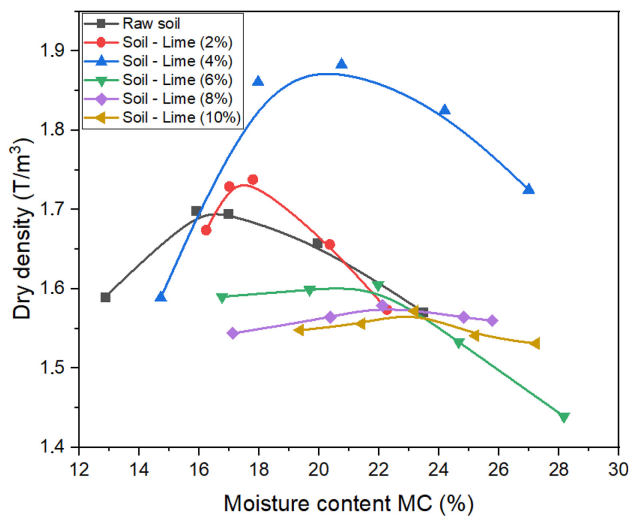


Figure 12. Determination of the compaction energy of raw soil and mixtures.

The Proctor test (Figure 12) is used to determine the optimum moisture content at which compaction leads to maximum dry density. This maximum dry density is not a direct indication of mechanical strength. However, for a material with fewer pores, there is more interaction between the grains, giving the soil good cohesion [1].

Experience shows that when soil is compacted according to a well-defined standard process at different water contents, the dry density of the material changes.

In fact, the more clayey the soil, the more water is needed to make it plastic. On the other hand, with these high-water contents, there is a risk of significant shrinkage during drying, causing the material to crack [1].

The addition of quicklime to silty clay shifts the dry densities towards the highest water contents, and the curves flatten out due to the decrease in clay content, which is compensated by the increase in sand content [8] [12].

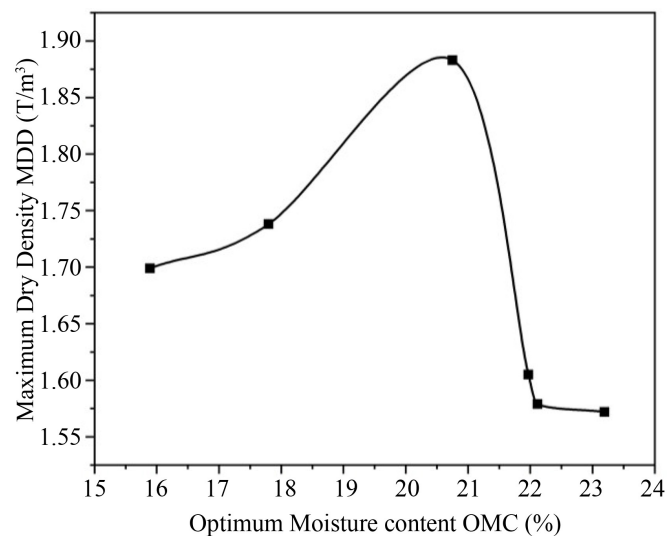


Figure 13. Determination of maximum dry density based on optimum moisture content.

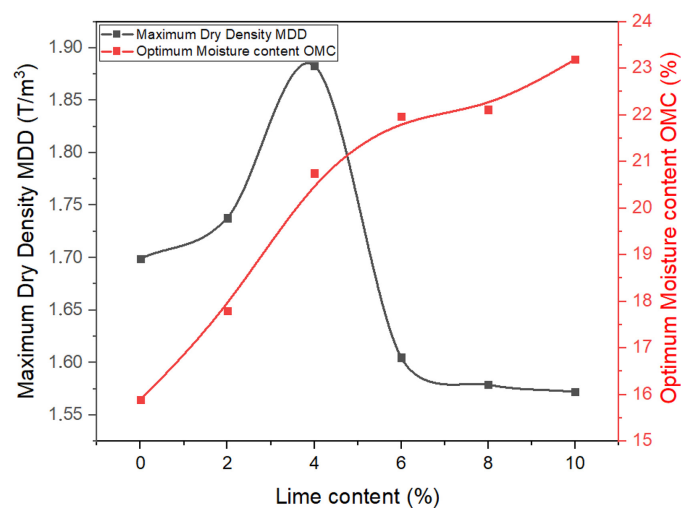


Figure 14. Evolution of maximum dry density and optimum water content as a function of lime content.

The maximum dry density correlates with the optimum water content shown in **Figure 13**.

According to **Figure 13** and **Figure 14**, for lime contents between 0% (silty clay) and 4%, the maximum dry density increases by 10% until it reaches a maximum of 1.88 T/m^3 at 4% lime. Above 4% lime, the maximum dry density no longer improves, but decreases by 16.52%.

The 4% quicklime content appears to be the fixing point for quicklime, above which the mechanical properties of the mixtures no longer improve [8].

According to **Figure 14**, the optimum water content of the mixture increases with the addition of quicklime, which is a hydrophilic material and causes a chemical reaction that releases a lot of heat and requires a lot of water [8] [12]. Several studies have shown that adding lime to clay soils reduces the maximum dry density and that, despite this reduction, the mechanical properties of the soil improve up to the point of lime setting. Beyond the point of lime setting, the mechanical properties of the soil no longer improve.

However, mixing silty clay with quicklime increases the maximum dry density up to a lime content of 4% and improves the mechanical properties of the material.

Beyond the setting point of lime, the maximum dry density and mechanical properties decrease.

The evolution of maximum dry density and CBR index as a function of lime addition to silty clay is strongly correlated (**Figure 14** and **Figure 15**).

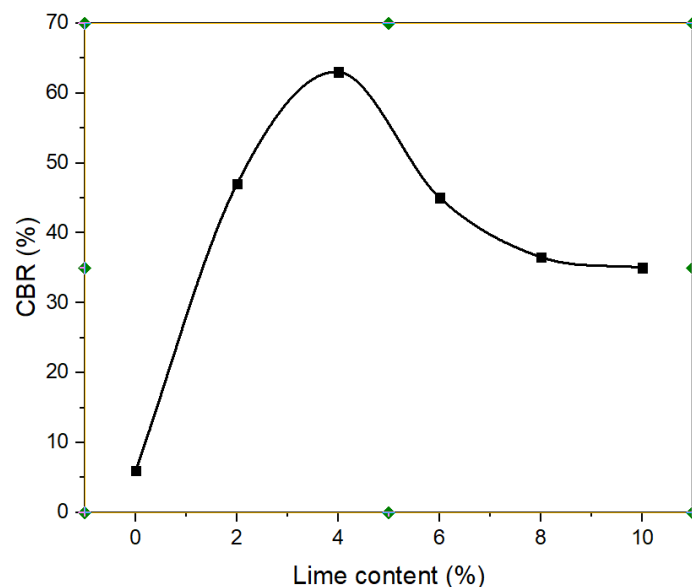


Figure 15. Evolution of the CBR index according to lime content.

According to **Figure 15**, the evolution of the CBR index is identical to that of the maximum dry density and their maximum is obtained at 4%, which corresponds to the setting point of the lime. Above 4% lime, the CBR index no longer improves but decreases. For lime contents between 0% and 4%, the CBR index increases from 6.5% to 63%, *i.e.* an increase of 969.23%, and for lime contents

between 4% and 10%, the CBR index decreases from 63% to 35%, i.e. a decrease of 55%.

The correlation between the variation in the CBR index and the maximum dry density is illustrated in **Figure 16**.

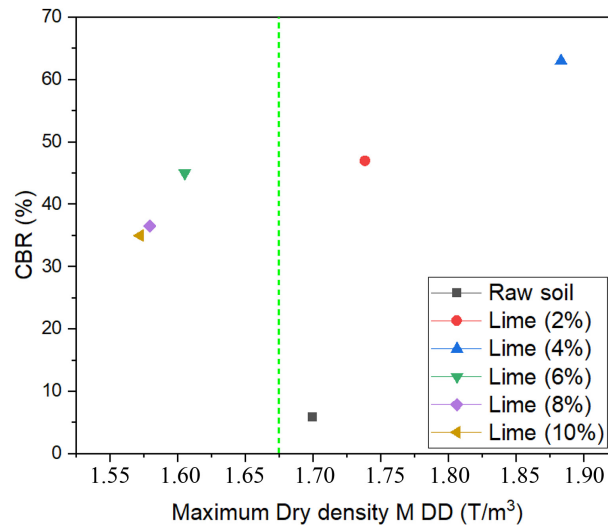


Figure 16. Determination of CBR based on maximum dry density.

Figure 16 shows that when the lime content increases from 0% (natural soil) to 4%, the maximum dry density and CBR increase by D_{smax} (1.70 - 1.90 T/m³) and CBR (6.5% - 63%) respectively. When the lime content increases from 6% to 10%, the maximum dry density decreases by D_{smax} (1.61 - 1.57 T/m³) and the CBR (45% - 35%). The maximum dry density and maximum CBR are obtained at 4%, which is considered to be the lime setting point. The uses of CBR based on the plasticity of the material for road construction are illustrated in **Figure 17**.

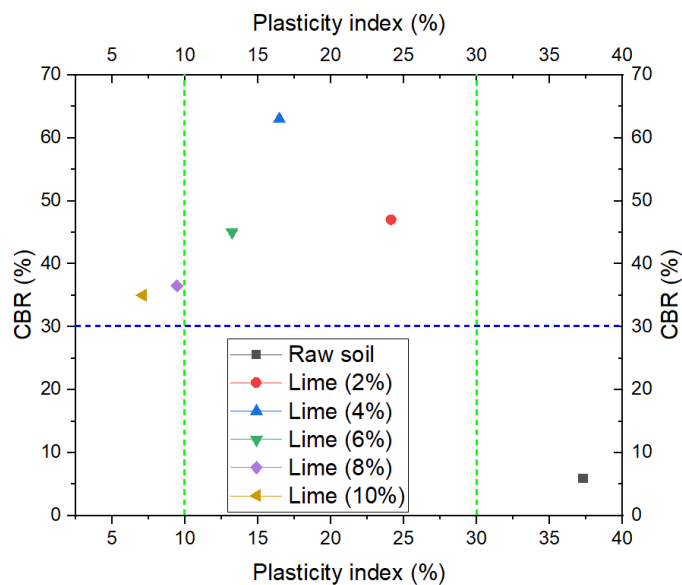


Figure 17. Use of CBR in foundation layers.

The CEBTP 1980 guide [32] for pavement design in tropical countries recommends that, to be used as a pavement foundation layer, a material must have a CBR $\geq 30\%$ and a CBR $\geq 80\%$ for the base layer. Given that the maximum CBR obtained is 63%, this material can only be used as a foundation layer or on car parks, provided that its plasticity index is greater than 10% but less than 30% CEBTP (1980) [32]. Thus, mixtures of 2%, 4% and 6% with CBR indices greater than 30% and plasticity indices between 13.22% and 24.12% are recommended for use as a foundation layer or on car park platforms.

3.2. Discussion

According to **Table 3**, which presents the AASHTO [22] and USCS [23] classification based on particle size distribution and Atterberg limits for natural soils and mixtures, the soils are classified as Class A-6 silty clay with a lime content of 0% to 6% and Class A-4 sandy silt with a lime content of 8% to 10%. According to **Table 5**, the classification based on the blue value of the soil gives us very clayey soils for a lime content of 0% to 4% and clayey silty soils for a lime content of 6% to 10%. As the natural soil consists of silty clay, the classification based on the soil's blue value takes precedence over the classification based on grain size and Atterberg limits.

The lime acted on the silty clay by modifying the particle size distribution, reducing the clay fraction and increasing the sand fraction (**Figure 4**). Authors Louis Ahouet *et al.* (2023) [8] obtained the same result, with the difference that their silt content decreased, whereas in this study it increased up to a lime content of 8% and decreased at 10% lime. Furthermore, according to **Table 3**, the addition of lime modifies the class and nature of the materials.

This difference in the behavior of the mixtures can be explained by the nature of the material, quicklime, and the mineralogy of the soil [8]. Indeed, despite the decrease in clay content, soil-lime mixtures remain expansive, as soil swelling does not depend on clay content [8].

The soil-quicklime mixture does not follow the law of mixtures (**Figure 8**). Indeed, Louis Ahouet *et al.* 2023 [8] found that while the plasticity index of the mixture was proportional to the clay content of the mixture, it was also proportional to the lime content of the mixture, but this is not the case.

In **Figure 9**, the addition of quicklime modifies the behavior of the Atterberg limits by increasing the plasticity limit and decreasing the liquidity limit. Several authors have shown that the increase in the plasticity limit of a treated soil may depend on the mineralogy of the clay and that these changes do not depend on the lime content and may be related to changes in cation exchange capacity (CEC) [8] [35] [36].

According to **Figure 13**, the specific surface area (SSA) and cation exchange capacity (CEC) of the clay fraction of the soil decrease with the addition of quicklime, and the two intrinsic properties of the two parameters were strongly correlated (**Figure 11**). The authors Herzog and Mitchell (1963) [37] and Diamond and

Kinter (1965) [38] found that changes in the fundamental properties (SSA, CEC) of the soil depended on the flocculation and agglomeration of clay particles into stable aggregates.

In **Figure 12**, adding 2% to 6% quicklime increases the maximum dry density despite the increase in the sand content of the mixture, and the particle size distribution curves remain parabolic. Above 4% lime, the dry density decreases, the sand content continues to increase, and the particle size distribution curves flatten and shift towards higher water contents [8] [12]. The lime content of 4% is considered to be the setting point of the lime (**Figures 13-15**).

According to **Figure 16**, mixtures at 2%, 4% and 6% have CBR indices greater than 30% and the material has a plasticity greater than the minimum of 10% and greater than the maximum of 30%. It can therefore be used as a road foundation layer in accordance with the recommendations of CEBTP 1980 [32].

4. Conclusions

The particle size distribution of natural soils and mixtures is poorly calibrated. As natural soils consist of silty clay, classification based on the blue value of the soil takes precedence over classification based on particle size and Atterberg limits. Lime modifies the rheology of mixtures through flocculation, with a reduction in clay and silt fractions, which is partially offset by an increase in the sand fraction. Despite the addition of 2% to 10%, the mixtures remain expansive in the presence of water, which explains the inactivity of the natural soil and mixtures.

The clay-silt-quicklime mixture does not follow the law of mixtures; in fact, if the plasticity index of the mixture was proportional to the clay content of the mixture, it would also be proportional to the lime content of the mixture. Variations in the Atterberg limits of the soil-lime pair do not depend on the hardening time, but on the lime content and are linked to variations in the intrinsic properties (CEC, SSA) of the mixtures, which are interdependent.

The addition of lime increases density for lime contents between 0% and 4%, beyond which dry density decreases, with a lime content of 4% being considered the setting point of the lime. Density shifts towards higher water contents and their curves flatten, thus improving the handling properties of the material.

Geotechnical properties have been developed to understand, for example, the relationship between maximum dry density and CBR index as a function of lime addition. The choice of CBR index based on the plasticity of the mixtures made it possible to select mixtures with a CBR between 45% and 63%, obtained with lime contents of 2% to 6%, which can be used as a foundation layer for pavements and to improve road platforms or car parks.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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